TIME DEPENDENCE OF GASEOUS RECOVERY

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Summary

For spark gap switches to operate at high repetition rates, it is necessary that the gas recover quickly. Recovery is controlled by the intrinsic properties of the gas or by gas removal. If the gas is not removed, the subsequent pulses see a decaying and cooling plasma, and the breakdown voltage is determined by the state of the discharge column. A phenomenological analysis is applied to the discharge volume to aid in understanding the character of the intrinsic recovery. The analysis is based on a definition for time-dependent recovery which includes the effects of cooling and charge recombinations. Results are compared to experimental data.

Introduction

The breakdown conditions for a gas-filled spark gap have been studied for many years. For a single pulse mode of operation, it is generally found that for static applied voltages the sparking potential is determined by Paschen's law. The explanation of the law is based on the Townsend avalanche theory with a menagerie of processes leading to secondary electron emission.[1] The many coefficients appearing in the breakdown criterion are functions of the ratio of electric field to gas density (E/N) for a given gas and electrode material.

When the applied voltage has a steep rise, the avalanche conditions are complicated by the time-dependent electric field. Also, when overvoltages are applied, breakdown proceeds via streamer formation requiring a critical number of electrons.[2,3] The details of streamer development and propagation are still being worked on.[4]

If a spark gap is operating in a repetitive-pulse mode, then succeeding pulses see a heated region of gas in the plasma state. For short times after the spark discharge, free electrons and positive ions are in abundance for the Townsend primary and secondary electron processes; however, those charges also distort the local electric fields. The density of gas in the discharge region is low due to current heating, but it is increasing due to cooling. The molecular constituents have changed through the collisional chemistry among charged, neutral and excited particles. Therefore, the complexity of the post-discharge state and processes makes it difficult to derive a breakdown criterion for addressing dielectric strength as in the single pulse case. An alternative is to write a time-dependent expression for recovery which circumvents the breakdown criterion.

Analysis

There are two major processes affecting breakdown of a gas. One is the Paschen law giving the striking voltage as a function of the product of the gas density and gap spacing. This is based on the amplification of ionizations by an electron as it crosses the gap and on the production of electrons at the cathode by products of the avalanche. The other is the initial number of electrons available for the applied field to work on. Thus it seems reasonable to assume that a gap has recovered when both of two things have occurred:

(1) The density of the discharge column has returned to the density of the gap (i.e., the gas has returned to the same point on the Paschen curve).

(2) The discharge column has returned to neutrality (i.e., the gas has returned to the initial avalanche conditions).

The two conditions can be combined into one expression defining the percent recovery R(t) as

$$R(t) = \frac{\rho_n(t)}{\rho_c(\infty)} \qquad (1)$$

where $\rho_n(t)$ is the neutral particle density at time t and $\rho_c(\infty)$ is the total particle density at $t\to\infty$ of the discharge column. That is, before the discharge consider an imaginary column with radius that will be determined by the predischarge processes. The total number of particles in this column gives the density $\rho_c(\infty)$. As the discharge develops, some neutral particles are ionized into charged particle pairs, and the heating expands the volume. With complete ionization, $\rho_n(o)=0$ giving $R(o)=0$; whereas with no ionization, $\rho_n(o)<\rho_n(\infty)$ giving $R(o)<1$, which is consistent with Paschen's law. For $t\to\infty$, the volume has cooled to its initial density, and all charged particle pairs have recombined so that $R(\infty)=1$. The total density of the volume at any time is given by

$$\rho_c(t) = \rho_n(t) + \sum_s \rho^*_{n,s}(t) + \rho_i(t)$$

where $\rho^*_{n,s}(t)$ is the partial density of excited neutrals of species s (e.g., metastables) and $\rho_i(t)$ is the partial density of charge particle pairs. However, using only the charge particle pair density in the recovery expression is a gross underestimate of the effect of the electrons. A gain factor should be added since even low electron densities contribute significantly when a high field is applied. A gain factor can be estimated from the Rather criterion for streamer formation. If $\alpha-\eta$ is the number of free electrons produced per unit length in an avalanche, then a streamer develops when

$$\exp\int_o^{x_c} (\alpha - \eta)dx = 10^8$$

where x_c is some critical length, α = Townsend's first ionization coefficient and η = electron attachment coefficient. This can be approximated by

$$\alpha x_c = 20$$

Thus each electron present in the gap is worth approximately 20 electrons when a field is applied and an avalanche is developed leading to streamer breakdown. Thus a gain factor $g \simeq 20$ can be introduced with the charge pair density which allows the percent recovery to be written as

$$R(t) = (\rho_c(t) - \sum_s \rho^*_{n,s}(t) - g\rho_i(t))/\rho_c(\infty) \qquad (2)$$

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The total particle density of the column $\rho_c(t)$, being composed of the ground state neutrals, the excited state neutrals and the positive ions of the charge particle pairs, is determined by the temperature of the column (assuming the temperature of the positive ions equals the temperature of the neutrals). Therefore, the total particle density is given by:

$$\rho_c(t) = \frac{T_g}{T_c(t)} \rho_c(\infty) \tag{3}$$

where T_g is the ambient gas temperature and $T_c(t)$ is the temperature of the column. Thus, the percent recovery can be written as

$$R(t) = \frac{T_g}{T_c(t)} - \frac{1}{\rho_c(\infty)} \sum_s \rho_{n,s}^*(t) - g \frac{\rho_i(t)}{\rho_c(\infty)}$$

$$= R_h(t) - R_n^*(t) - R_i(t) \tag{4}$$

where

$$R_h(t) = \frac{T_g}{T_c(t)}$$

is the recovery due to heat dissipation

$$R_n^*(t) = \frac{1}{\rho_c(\infty)} \sum_s \rho_{n,s}^*(t)$$

is the recovery due to excited state dissipation

$$R_i(t) = g \frac{\rho_i(t)}{\rho_c(\infty)}$$

is the recovery due to charge particle pair dissipation

$T_c(t)$ is determined by the thermal diffusion equation with electrode cooling. It should be noted that the thermal recovery term is identical to that derived purely algebraically from the Paschen curve by Rubchinskii.[5] The charge particle pair density for high densities is determined by

$$\dot{\rho}_i = -\nu_R^* \rho_i^2 - \nu_A \rho_i \tag{5}$$

where $\nu_R^* = \nu_R/m$, ν_R = electron-ion recombination coefficient, m = mass of the ions and ν_A = attachment rate. The solution of this equation gives for the charge particle pair recovery

$$R_i(t) = \frac{g \rho_i(o)/\rho_n(\infty) \; e^{-\nu_A t}}{1 + \rho_i(o) \frac{\nu_R^*}{\nu_A} (1 - e^{-\nu_A t})} \tag{6}$$

Assume that the initial number of charge particle pairs is some fraction of the total particles before the discharge resulting in

$$N_i(o) = f_i N_n(\infty)$$

The initial charge particle pair density is gotten by dividing the above by the initial volume

$$\frac{N_i(o)}{V(o)} = \rho_i(o) = \frac{f_i N_n(\infty)}{V(o)} = \frac{f_i N_n(\infty)}{V(\infty) \; T_c(o)/T_g}$$

This gives for the charge particle pair recovery

$$R_i(t) = \frac{g \; f_i \; T_{g/c} \; e^{-\nu_A t}}{1 + f_i N_n(\infty) \; T_{g/c} \frac{\nu_R}{\nu_A} (1 - e^{-\nu_A t})} \tag{7}$$

where $T_{g/c} = T_g/T_c(o)$.

The fractional ionization can be estimated through the Saha equation

$$\frac{N_i(T_o)}{N_n(T_o)} = \frac{1}{N_i(To)} \eta_{eV} \; T_o^{3/2} \; e^{-U_i/T_o} \tag{8}$$

where $T_o = T_c(o)$ in eV, $\eta_{eV} = \left(\frac{2\pi Me}{h^2}\right)^{3/2}$, Me = electron mass, h = Planck's constant and U_i = ionization energy. Define the constant $C(T_o)$ as

$$c(T_o) = \eta_{eV} \; T_o^{3/2} \; e^{-U_i/T_o}$$

then with $f_i = N_i(o)/N_n(\infty)$ and $N_n(T_o) = N_n(\infty) - N_i(o)$ equation (8) gives

$$f_i = -1/2 \; \tilde{C}(T_o) + \sqrt{\tilde{C}(T_o) + (1/2 \; \tilde{C}(T_o))^2} \tag{9}$$

where $\tilde{C}(T_o) = C(T_o)/N_n(\infty)$.

The excited state recovery for metastables is described from an equation of the form

$$\dot{\rho}_{n,s}^* = -\gamma N_n^2(t) \rho_{n,s} - \nu_m \rho_{n,s}^2$$

where γ is the three-body collision coefficient and ν_m is the metastable-metastable collision coefficient. Other terms could be added for more chemistry.

Returning to the thermal recovery term, the temperature of the column is controlled by the cooling due to radial heat diffusion in the gas and axial diffusion into the electrodes. Edels, et. al.[6] discuss the temperature recovery of an arc column and identify three temperature regimes in which different recovery processes dominate. Only the coolest regime (2000 ^oK > T > ambient) is analyzed via a simple lumped-components model. Using their characteristic time constants

τ_{gr} (gas radial heat flow) $\propto r_g^2/k_g$
τ_{er} (electrode radial heat flow) $\propto r_e^2/k_e$
τ_{ga} (gas axial heat flow) $\propto d^2/k_g$
τ_{ea} (electrode axial heat flow) $\propto \ell_p^2/k_e$

where

r_g = gas column radius
r_e = electrode radius
d = gas column length
ℓ_p = electrode heat-penetration depth

A parameter λ_τ can be defined as

$$\lambda_\tau = 1 - \frac{\frac{\tau_{gra}}{\tau_{gr}} - \frac{\tau_e}{\tau_{gr}} - (1 - T_{e/g})\left(\frac{\tau_{gra}}{\tau_a} + \frac{\tau_e}{\tau_a}\right)}{1 + \frac{\tau_{gra}}{\tau_e} + \frac{\tau_e}{\tau_{gra}}} \quad (10)$$

Then the percent recovery (ignoring the excited state term) can be written as

$$R(t) = \frac{1}{1 + T_{p/g}\left((1 + \lambda_\tau)e^{-\alpha t} - \lambda_\tau e^{-\beta t}\right)} - \frac{gf_i\, T_{g/c}\, e^{-t/\tau_A}}{1 + \frac{\tau_A}{\tau_R}\left(1 - e^{-t/\tau_A}\right)} \quad (11)$$

where

$$\alpha = \frac{1}{\tau_{gra} + \tau_e}$$

$$\beta = \frac{1}{\tau_e} + \frac{1}{\tau_{gra}}$$

$$\frac{1}{\tau_{gra}} = \frac{1}{\tau_{gr}} + \frac{1}{\tau_a}$$

$$\tau_a = (\tau_{ga}\, C_e + \tau_{ea}\, C_g + C_e\, C_g/a_c\, h_s)/(C_e + C_g)$$

$$\frac{1}{\tau_e} = \frac{1}{\tau_{ea}} - \frac{1}{\tau_{er} + C_e/a_e\, h_e}$$

with C_e and C_g the heat capacities of the electrode and gas, h_e the heat transfer function, and a_e and a_e the areas of the electrode heat-penetration and gas column. It can be seen that for very short times the limit of $R_H(t)$ is

$$\lim_{t \to o} R(t) = T_{g/c}\,(1 - gf_i) \quad (12)$$

with f_i given by equation (9). With respect to the denominator of $R_H(t)$, a parameter can be defined as

$$\lambda_D \equiv (1 + \lambda_\tau)e^{-\alpha t} - \lambda_\tau e^{-\beta t}$$

with β always greater than α. If the reciprocal of τ_e or τ_{gra} is very large, then $\beta >> \alpha$ and there results two cases:

$$\tau_{gra} << \tau_e,\ \lambda_D \simeq (1 + \lambda_\tau)e^{-t/\tau_e}$$

$$\tau_e << \tau_{gra},\ \lambda_D \simeq (1 + \lambda_\tau)e^{-t/\tau_{gra}}$$

Thus a general form for $R_H(t)$ can be used as

$$R_H(t) = \frac{1}{1 + Be^{-t/\tau_H}}$$

where

$$B = T_{p/g}\,(1 + \lambda_\tau)$$

$$\tau_H = \tau_e \text{ or } \tau_{gra}$$

It can be seen that for times short with respect to τ_H, but long compared to τ_A or τ_R, the value of R(t) is given by

$$R(t) \simeq \frac{1}{1 + B}$$

Thus from the data of the percent recovery as a function of time, a value for B can be obtained. Using the data of Moran, et. al.[7] for gases at atmospheric pressure, it is seen that $B \simeq 4$. Using these approximations and $\tau_H = 2X10^{-3}$ with $T_o = 30{,}000^oK$, Figure 1 shows how the equation for R(t) fits the data for various ν_R. The value $\nu_R = 2X10^{-12}\ S^{-1}$ is consistent with the literature.

Finally, if it is assumed that the post-discharge column cools via heat transfer out of the column so that the column radius remains approximately constant, then τ is directly proportional to the square of the column radius and thus decreases with pressure. Also, since the temperature of the column is proportional to the pressure, the value of B increases with temperature. Therefore, an increase in pressure causes the recovery curves to shift to the left and decrease for early times. Figure 2 shows the argon curve compared to data at a pressure of 35 atm for $\tau_H + 1.2X10^{-5}$ and B = 25.

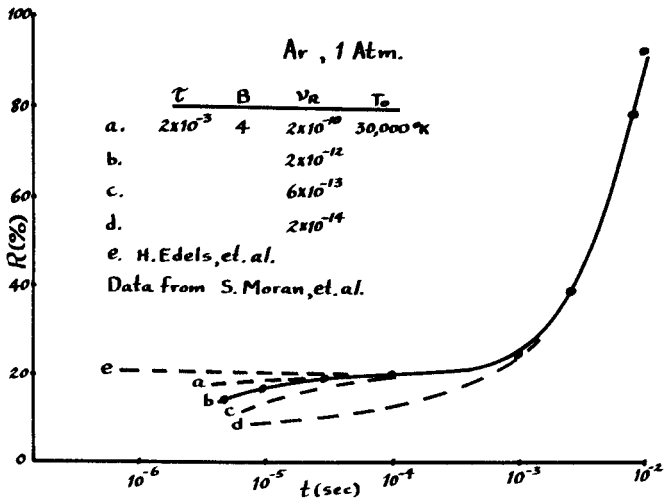

Figure 1. Percent recovery vs. time for Ar at 1 Atm. pressure.

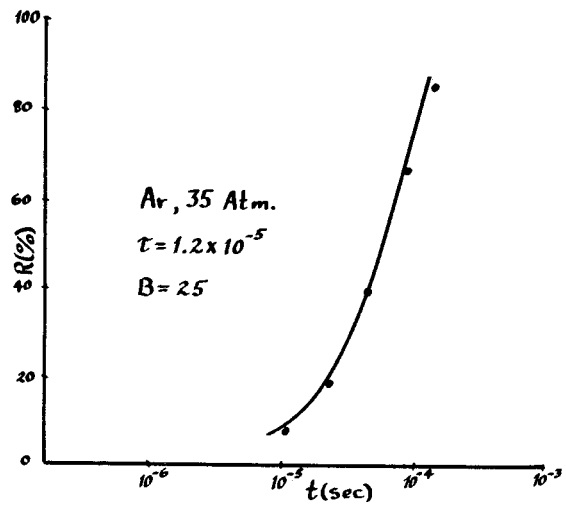

Figure 2. Percent recovery vs. time for Ar at 35 Atm. pressure.

Conclusion

A time-dependent, phenomenological definition of gaseous recovery was introduced based on the Paschen, Townsend and Rather breakdown processes. Reasonable values of the gas and electrode parameters lead to curves fitting the data. It appears in general that the recovery rate at long time is dominated by the cooling of the discharge column, while at short times it is dominated by recombination processes.

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